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(54) **RESONANT FIBER OPTIC BEAM MANIPULATOR**

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**G02B 6/42** (2006.01)  
**G02B 6/028** (2006.01)

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CPC ..... **G02B 6/4289** (2013.01); **G02B 6/028** (2013.01)

(58) **Field of Classification Search**

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See application file for complete search history.

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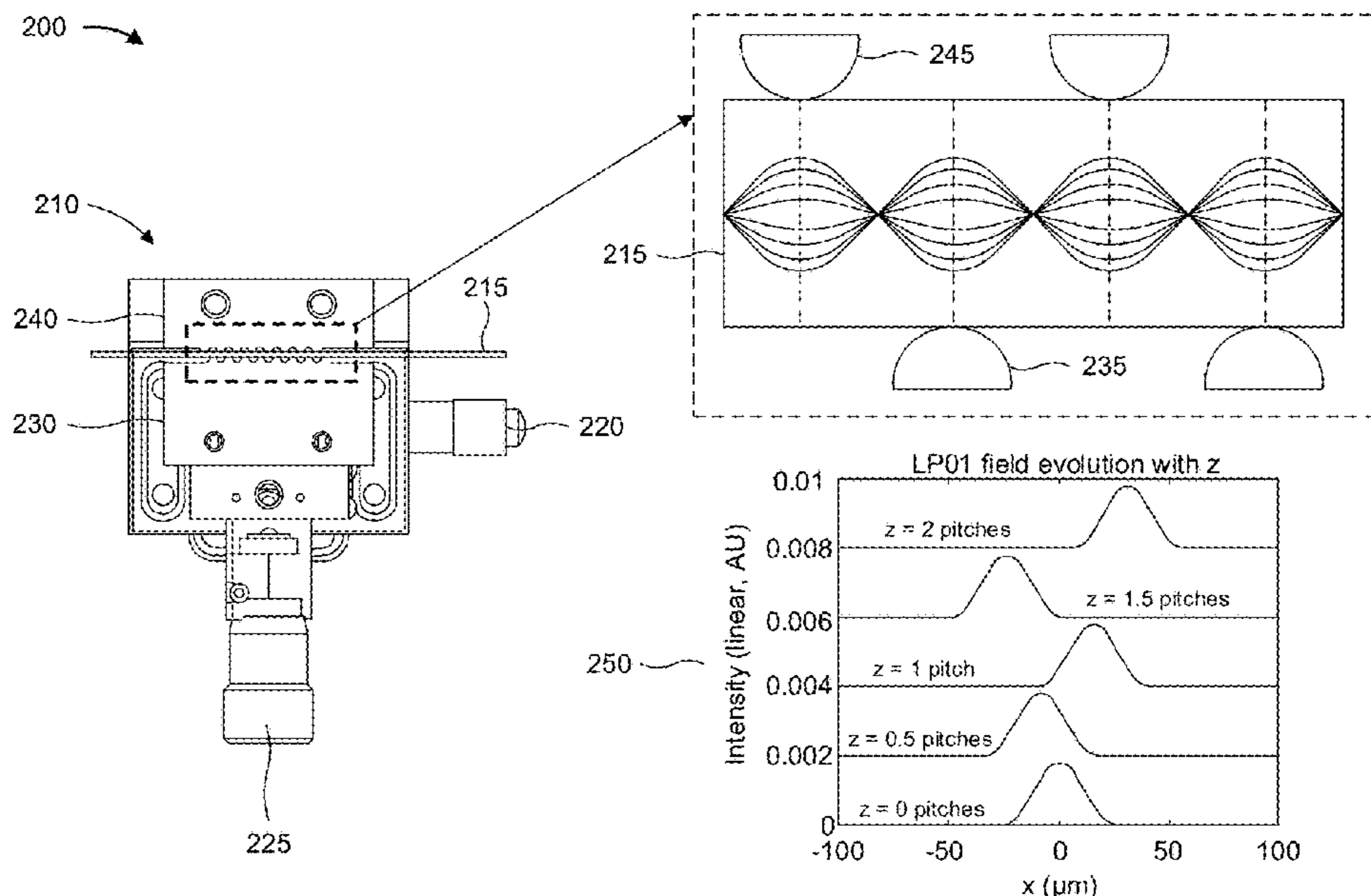
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(57) **ABSTRACT**

A graded index fiber having a refractive index profile that causes a beam to be re-imaged in the graded index fiber with a regular period may include a set of bends that have a bend period matched to or nearly matched to a pitch of the graded index fiber. For example, the set of bends may be formed in the graded index fiber using one or more bending devices that include one or more protrusions that have a periodicity matched to or nearly matched to a pitch of the graded index fiber. A first section of the one or more bending devices may be actuated to move towards a second section of the one or more bending devices such that the one or more protrusions cause the bends to be formed in the graded index fiber.

**20 Claims, 7 Drawing Sheets**



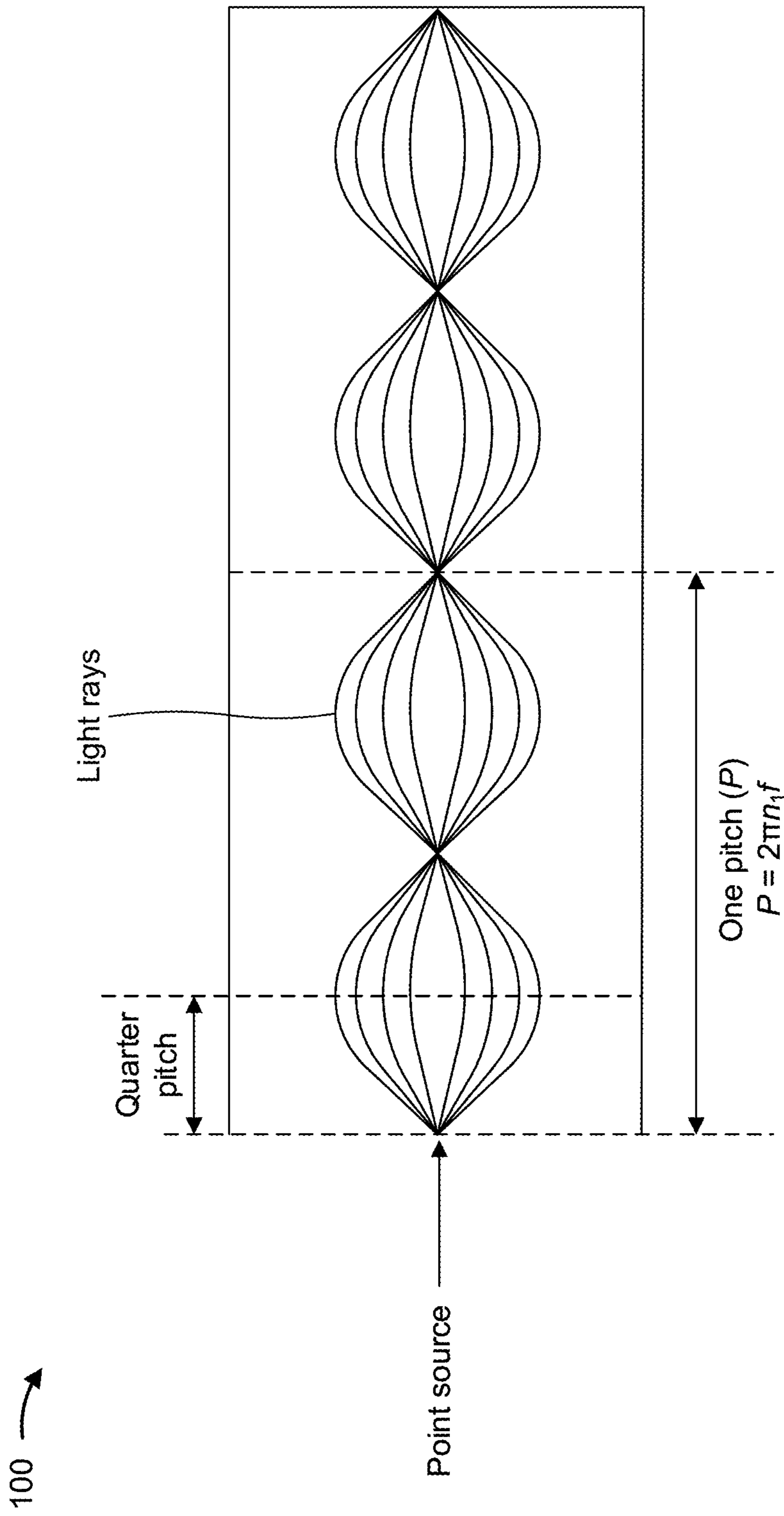


FIG. 1

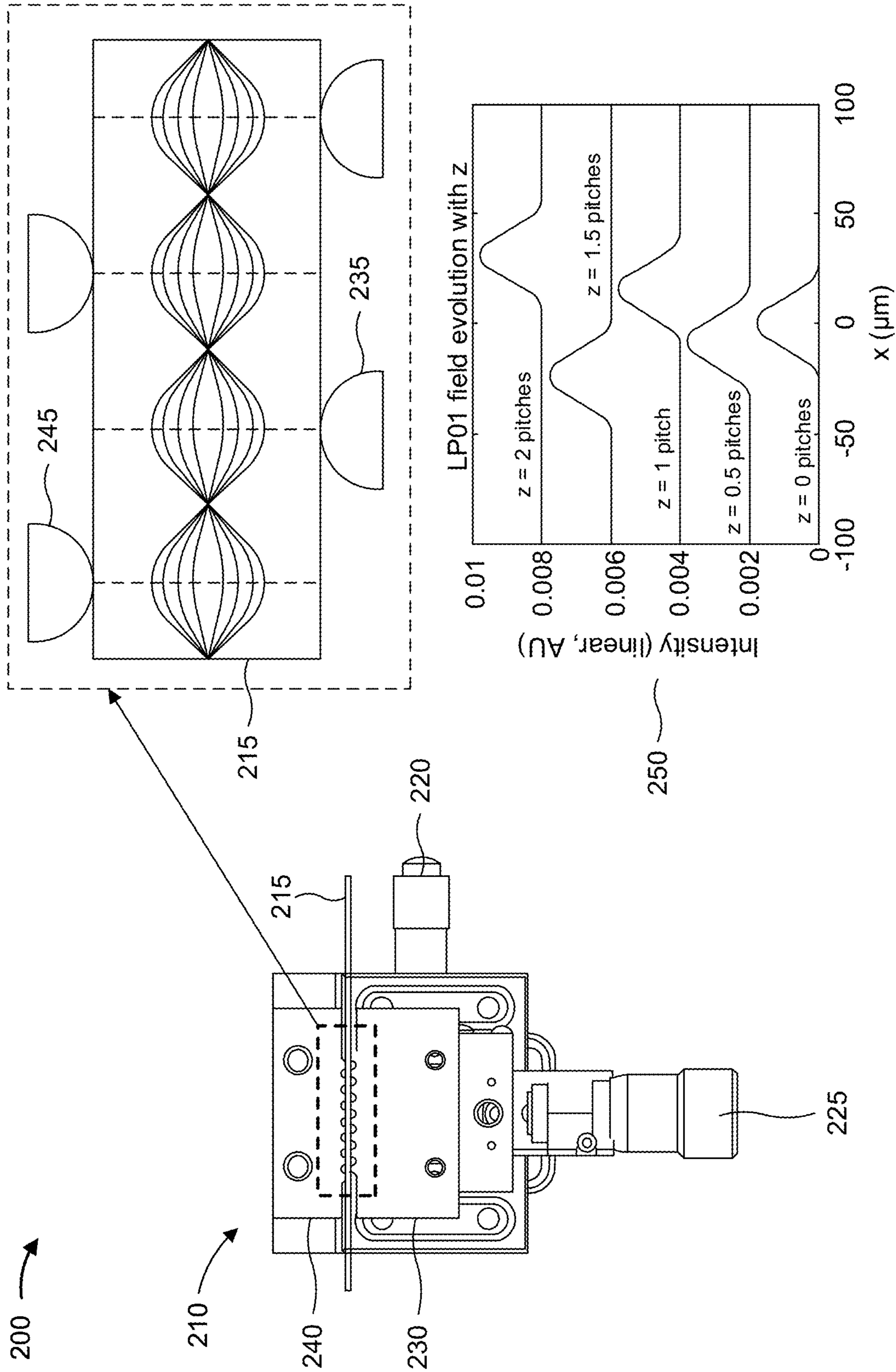


FIG. 2

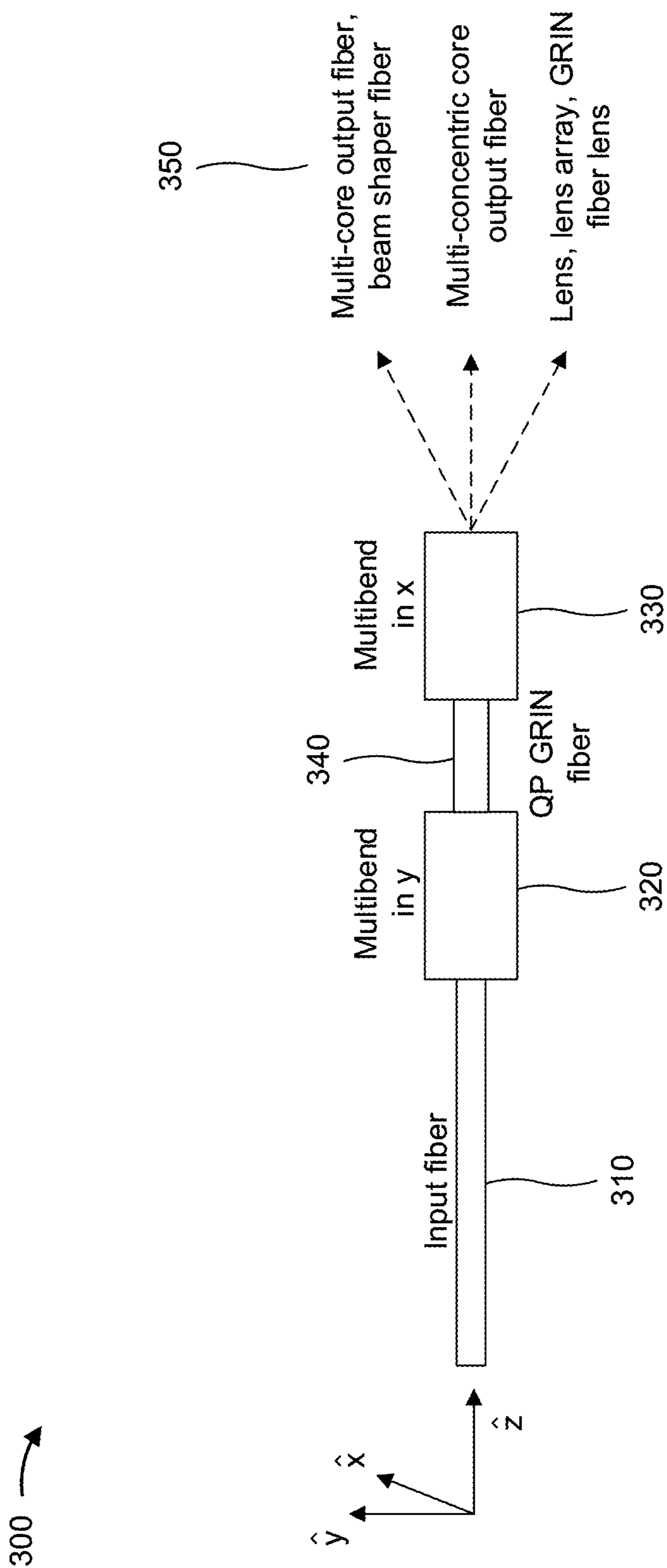


FIG. 3

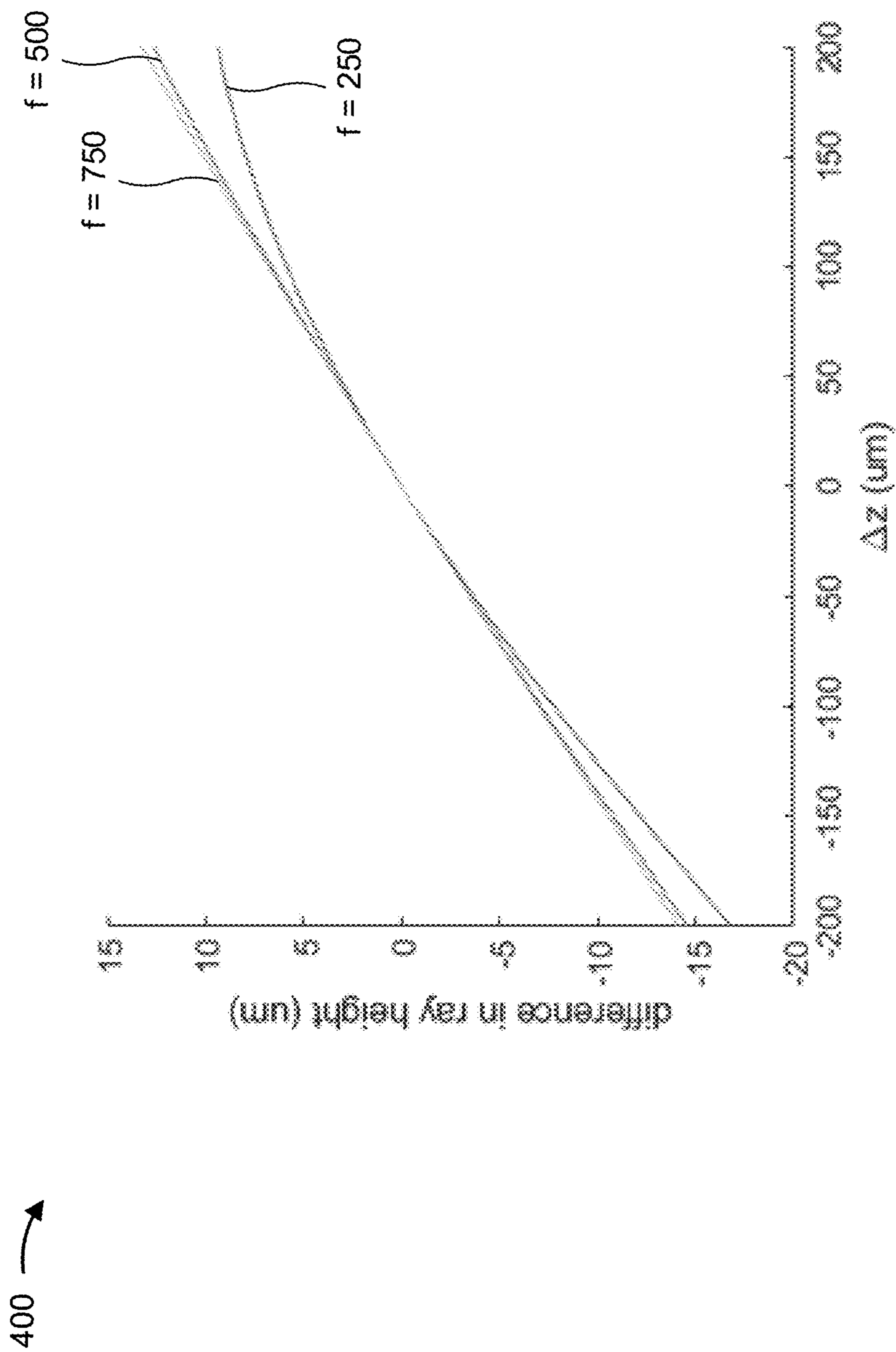


FIG. 4A

410 →

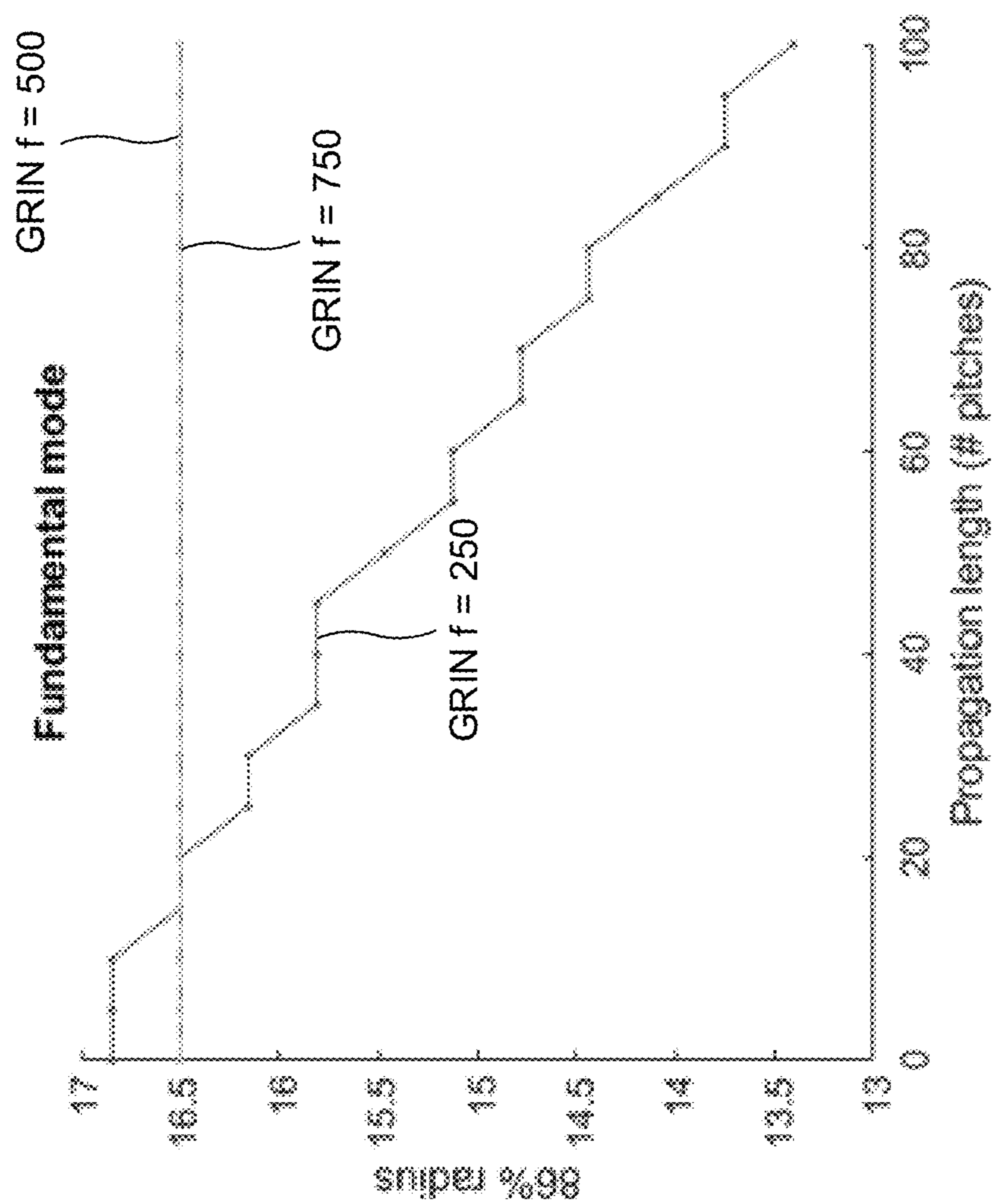


FIG. 4B

420 →

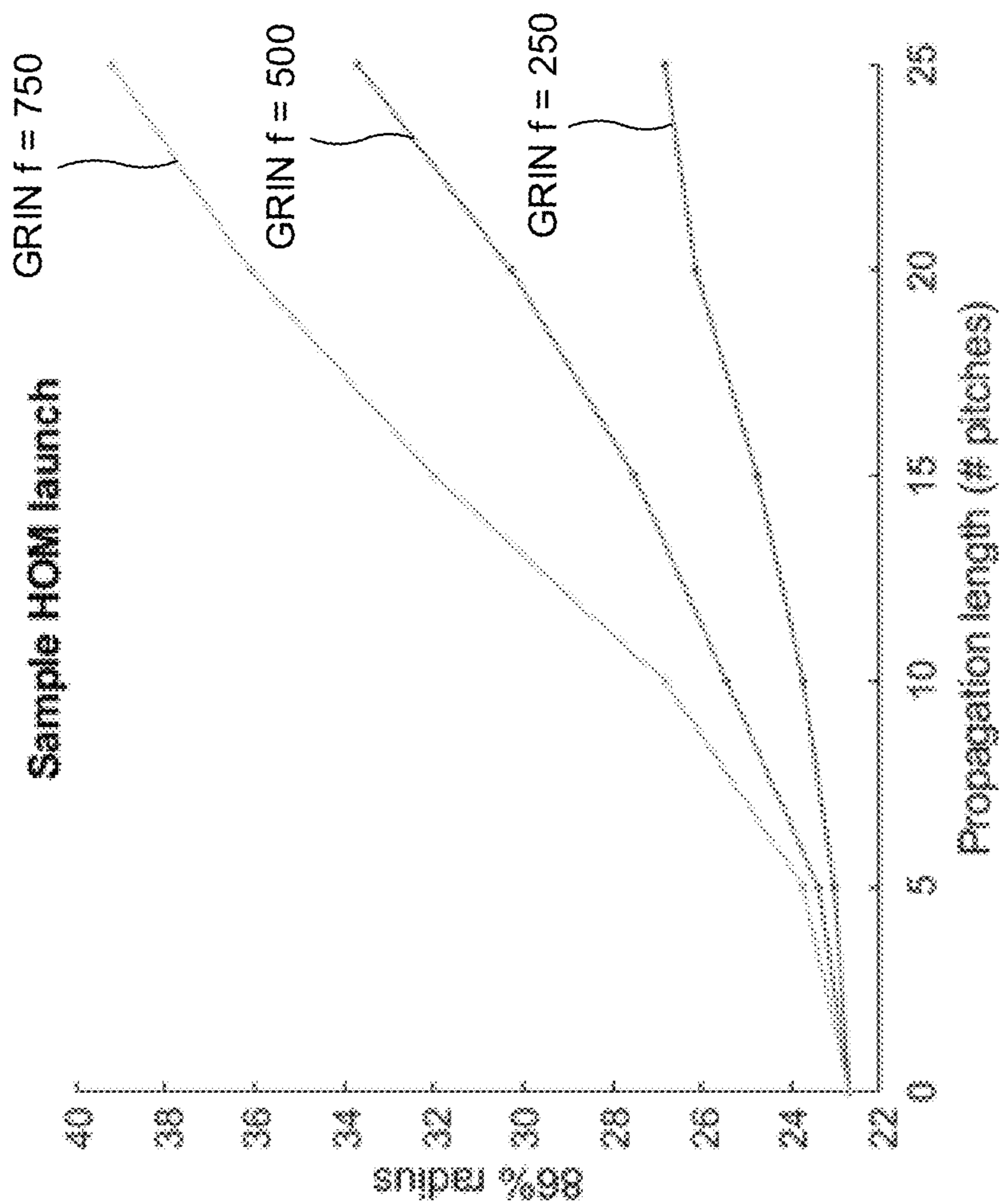
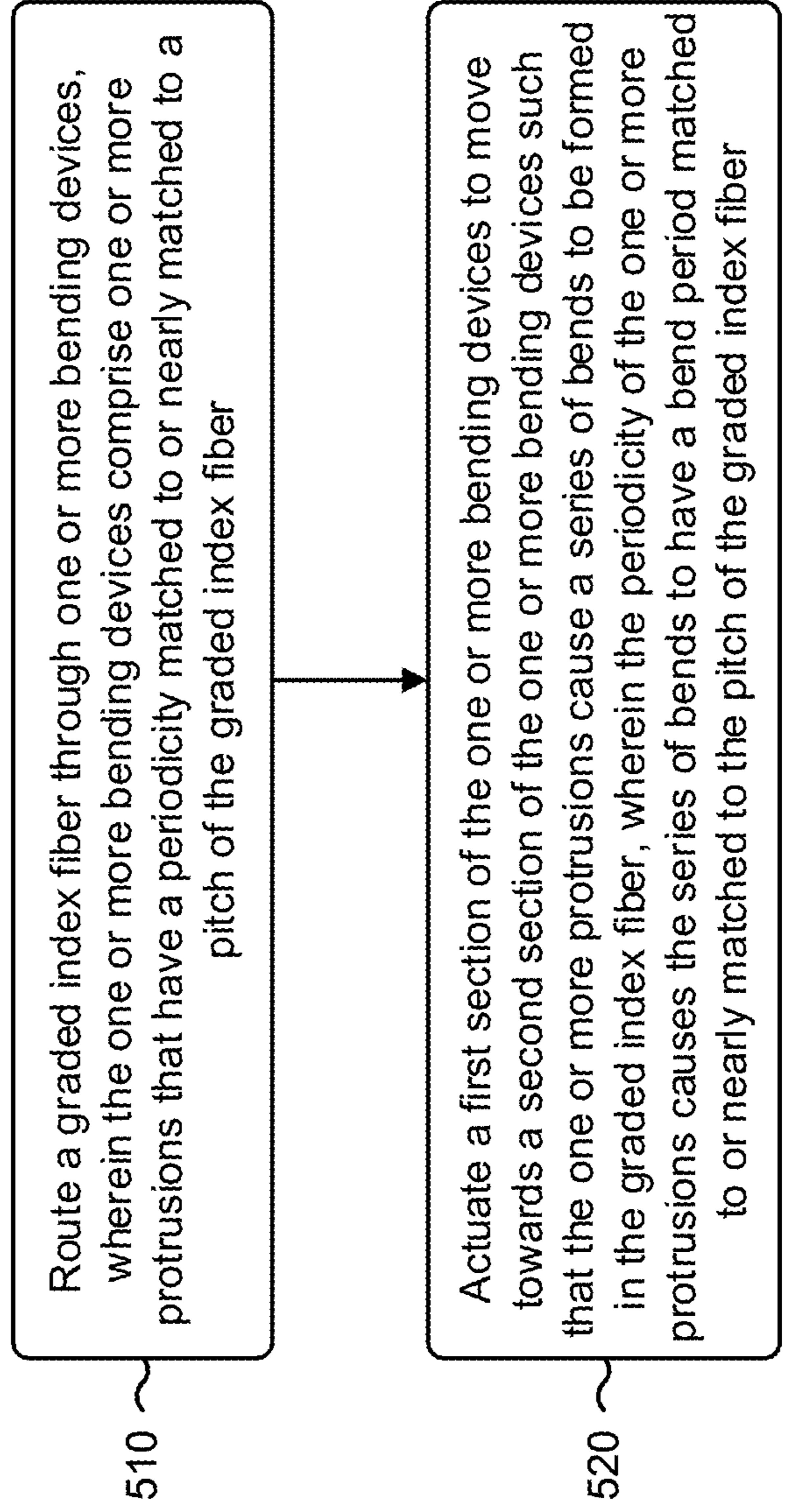


FIG. 4C

500 →



**FIG. 5**



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## RESONANT FIBER OPTIC BEAM MANIPULATOR

### RELATED APPLICATION

This application claims the benefit of U.S. Provisional Patent Application No. 63/032,219, entitled "RESONANT FIBER OPTIC BEAM MANIPULATOR," filed May 29, 2020, the content of which is incorporated by reference herein in its entirety.

### TECHNICAL FIELD

The present disclosure generally relates to steering or otherwise routing an optical beam through an optical fiber, and more particularly, to steering or otherwise routing an optical beam through a graded index fiber with a set of bends that have a bend period matched to or nearly matched to a pitch of the graded index fiber.

### BACKGROUND

Laser material processing can be used for cutting, drilling, welding, brazing, surface annealing, alloying, hardening, and/or other applications. In particular, laser material processing generally includes using one or more optical fibers to deliver a high-power and/or high-intensity laser beam to a workpiece on which the laser material processing is to be performed. For example, a typical fiber-delivered laser material processing system may include a laser source (e.g., one or more fiber laser modules), an optical coupler unit, a delivery fiber (typically 10-50 meters in length and included in a delivery cable that may be pluggable on one or both ends), and a processing head. The processing head is an optical assembly that includes a receptacle for the delivery fiber, optics for projecting the laser power, and any components needed for laser-based processing. In operation, the laser source transmits a laser light emission into the optical coupler unit (e.g., through free space or through a separate optical fiber), and the optical coupler unit, which may internally transmit the emission through optical fiber or through free space, and which may magnify or de-magnify the emission, couples the laser light emission into the delivery fiber. The delivery fiber then transmits the laser light to the processing head, which projects the laser light onto a workpiece in association with performing the material processing task. Accordingly, advantages of laser material processing may include high productivity, a non-contact nature of processing, improved quality, high precision and mobility of a delivery point of the laser beam, and/or the like.

One challenge that arises in the context of laser material processing relates to fiber beam shaping (e.g., for cutting, welding, and/or the like), which is an increasingly important aspect of high-power laser material processing. For example, in some cases, the high power and excellent beam quality of fiber lasers may be leveraged to perform "keyhole welding" with high aspect ratio penetration profiles in narrow fusion zones with low distortion and minimal heat-affected zones. In other examples, a larger laser spot size with a lower power density can be used to perform shallower "conduction welding" that may be used for aesthetic welds, to minimize a need for post-processing steps, and/or the like. In still other examples, processing different materials, or materials with different thicknesses, may require different properties in an optical beam (e.g., a high-brightness, small spot size may be desired for some materials, while other

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materials may require a larger, higher-divergence beam). Accordingly, a laser system with beam shaping capabilities and capabilities to cycle or otherwise transition among multiple states in order to control and/or vary the properties of an optical beam may be desirable.

### SUMMARY

According to some implementations, an optical assembly may include: an input fiber to provide a beam; and a graded index fiber, coupled to the input fiber, having a refractive index profile that causes the beam to be re-imaged in the graded index fiber with a regular period having a pitch length, wherein the graded index fiber comprises a set of bends that have a bend period matched to or nearly matched to the pitch length of the graded index fiber.

According to some implementations, a method may include: routing a graded index fiber through one or more bending devices, wherein the one or more bending devices comprise one or more protrusions that have a periodicity matched to or nearly matched to a pitch of the graded index fiber; and actuating a first section of the one or more bending devices to move towards a second section of the one or more bending devices such that the one or more protrusions cause a series of bends to be formed in the graded index fiber, wherein the periodicity of the one or more protrusions causes the series of bends to have a bend period matched to or nearly matched to the pitch of the graded index fiber.

According to some implementations, a bending device may include: an adjustment stage adapted to receive a graded index fiber, wherein the adjustment stage comprises a first section having a first set of protrusions and a second section having a second set of protrusions that have a periodicity matched to or nearly matched to a pitch of the graded index fiber; and an actuation mechanism to cause the first section of the adjustment stage to move toward the second section of the adjustment stage such that the first set of protrusions and the second set of protrusions cause a series of bends to be formed in the graded index fiber.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram of a graded index fiber.

FIG. 2 is a diagram of one or more example implementations of a bending device that can be used to apply one or more bends in a graded index fiber.

FIG. 3 is a diagram of one or more example implementations of multiple bending devices arranged in a cascaded configuration.

FIGS. 4A-4C are example plots related to a propagation length of a graded index fiber manipulated using bending devices and methods described herein.

FIG. 5 is a flowchart of an example process for applying a set of bends in a graded index fiber using one or more bending devices.

### DETAILED DESCRIPTION

The following detailed description of example implementations refers to the accompanying drawings. The same reference numbers in different drawings may identify the same or similar elements.

As described above, fiber beam shaping is an increasingly important aspect of high-power (e.g., greater than 100 watts (W)) laser material processing and/or other applications where a rasterable fiber source may be desirable (e.g., light detection and ranging (LIDAR), endoscopic microscopy,

and/or the like). For example, a laser that can control and vary beam properties is desirable in the context of laser material processing because different materials, or materials with different thicknesses, may require different properties in an optical beam. For example, a high-brightness, small spot is generally desired for thin stainless steel (e.g., stainless steel with a thickness of less than 3 millimeters (mm)), whereas a larger, higher-divergence beam may be desired for thicker mild steel (e.g., steel with a thickness of more than 12 mm).

Accordingly, an important factor in designing a laser system with beam shaping capabilities is to provide the ability to cycle or otherwise transition among multiple states that produce optical beams with different properties. However, an actuation method is needed to toggle among the different states, which presents a challenge for kilowatt (kW) lasers because the actuation method must be essentially lossless. For example, switches used in telecom and/or datacom applications can incur 0.5 decibels (dB) of loss or more, which is unacceptable for such high powers. The need to provide a lossless actuation method to toggle among different states, in addition to the desirability of keeping the entire system in-fiber for improved manufacturability and reduced alignment tolerances, greatly restricts possible actuation options. Although one simple actuation approach may be to have two laser engines that can be independently turned on and off, this actuation approach significantly increases system cost.

Graded index fibers present one possible alternative to having two independently controlled laser engines. In particular, a graded index fiber generally has a refractive index profile, a square of which is parabolic or near-parabolic, as shown in the following expression:

$$n^2 = n_1^2 - \frac{r^2}{f^2}; r \leq r_{clad}$$

where  $n_1$  is a peak (or maximum) refractive index,  $r$  is a radial coordinate (e.g., a distance from a center of the graded index fiber), and  $f$  is a focal length of the graded index fiber, as related to a pitch of the graded index fiber. Accordingly, bending a graded index fiber generally results in a translation of the beam center, proportional to the curvature of the bend (1/the local bend radius ( $R_{bend}$ )). The displacement ( $\Delta x$ ) is also dependent on properties of the graded index fiber, such as the focal length ( $f$ ) and the peak/maximum refractive index ( $n_1$ ) of the graded index fiber, as shown in the following expression:

$$\Delta x = \frac{n_1^2 f^2}{R_{bend}}$$

Thus, one potential method to provide an all-in-fiber beam switch is to use a graded index fiber and bend the graded index fiber adiabatically to varying degrees, such that different beam offset positions inside the fiber can be achieved depending on the curvature of the bend. However, for large offsets, adiabatic bending requires long lengths of bent fiber and large overall bend angles, and may cause significant stress on the fiber, which may lead to breakage. Moreover, if such a shift is desired to achieve a variable-offset launch into a second fiber (e.g., a multicore fiber, a multi-rotary fiber, and/or the like), the stress occurs exactly

at a splice point, which makes splice optimization more difficult, and makes the splice more prone to failure.

Some implementations described herein relate to a device and method that use a periodic reimaging property of a graded index fiber to route an optical beam within an optical fiber or translate an optical beam in space using a well-controlled series of bends. In this way, by using a series of smaller-strength bends rather than a single long adiabatic bend, some implementations described herein may enable a larger range of beam steering (e.g., relative to a single bend), because large bends may be limited by local stress applied to the optical fiber. Additionally, or alternatively, a single short bend at a well-controlled position (rather than a series of bends) may be formed in the graded index fiber, which may reduce stress on the graded index fiber and reduce the need for the bend apparatus to be precisely tailored to the periodicity or pitch of a particular graded index fiber. Furthermore, by routing the optical beam within an optical fiber, some implementations described herein may eliminate or reduce input/output coupling loss into the routing device, and improve manufacturability with reduced alignment tolerances. Additionally, some implementations described herein can be used to route beams in both space and angle, enabling controlled two-dimensional beam steering out of an optical fiber. In some implementations, the device and method described herein may be used in kW fiber beam shaping or in other fields such as LIDAR, endoscopic microscopy, and/or any other suitable application in which a rasterable fiber source may be desirable.

FIG. 1 illustrates an example 100 of a graded index fiber. More particularly, as described herein, a square of a refractive index profile of a graded index fiber may be parabolic or near-parabolic (e.g., in a core region), where the refractive index varies smoothly in a radial direction from an axis of the graded index fiber to a certain radial position. In other words, the graded index fiber has a refractive index profile that is parabolic or near-parabolic in cross-section, and uniform along a length of the graded index fiber. Accordingly, light rays that propagate through the graded index fiber follow a periodic trajectory through the parabolic or near-parabolic refractive index profile of the graded index fiber. For example, as shown in FIG. 1, one or more light rays that originate from a point source (e.g., a laser source, an input fiber coupled to a laser source, and/or the like) may propagate through the graded index fiber.

Due to periodic imaging properties of the graded index fiber, the point source is exactly reimaged every pitch (and imaged but inverted every half-pitch). Mathematically, the light rays traveling through a single pitch of the graded index fiber are calculated as four successive Fourier transforms, representing collimation (e.g., in a first quarter-pitch), focusing to an inverted image (e.g., in a second quarter-pitch), collimation (e.g., in a third quarter-pitch), and focusing again (e.g., in a fourth quarter-pitch). In some implementations, the pitch of the graded index fiber is determined by a core diameter and a numerical aperture when the graded index fiber is drawn. In some implementations, as described herein, periodic bending of the graded index fiber, with a bend period matched to or nearly matched to a pitch of the graded index fiber, yields a much stronger and more versatile modification of the beam path, compared with adiabatic bending.

As indicated above, FIG. 1 is provided as an example. Other examples may differ from what is described with regard to FIG. 1.

FIG. 2 is a diagram of one or more example implementations 200 of a bending device 210 that can be used to apply

one or more bends in a graded index fiber **215**. In some implementations, as described herein, the bending device **210** may be designed to apply a series of bends to the graded index fiber **215** in alternating directions at every odd quarter-pitch (e.g., every half-pitch, starting from a first quarter-pitch) based on the periodic imaging behavior of the graded index fiber **215**. In this way, the series of bends may have a bend period that is matched to, or nearly matched to, a pitch of the graded index fiber **215**. For example, for a perfect fiber, the period of the bending device **210** would be equal to the pitch of the graded index fiber **215**. However, due to fiber manufacturing tolerances, the fabricated pitch can deviate from the nominal value. To correct for the deviation between the fabricated pitch and the nominal value, the bending device **210** may be fabricated to have a period that is shorter than the pitch of the graded index fiber **215**, and the bending device **210** may be placed on a rotation stage **220**. In some implementations, the rotation stage **220** may include a knob or other rotation mechanism to rotate the bending device **210** with respect to the graded index fiber **215** in order to elongate the effective period applied to the graded index fiber **215** and enable in-situ adjustments of the period of the perturbations that cause the bends to be formed in the graded index fiber **215**.

As described herein, for a given acceptable level of curvature to be imposed on the graded index fiber **215**, the bending device **210** may allow a beam to be displaced approximately  $4N$  times farther than using a single adiabatic bend, where  $N$  is a number of pitches in the graded index fiber **215**. In other words, for a targeted amount of beam offset, the bending device **210** enables the beam offset to be achieved using approximately  $\frac{1}{4}N$  times as much bend curvature on the graded index fiber **215**. Accordingly, the bending device **210** utilizes the bending properties of the graded index fiber **215** much more effectively than adiabatic bending. In this way, the bending device **210** imposes much less stress on the graded index fiber **215**, provides much greater performance, and significantly simplifies mechanical implementation.

As shown in FIG. 2, the graded index fiber **215**, which is nominally  $N$  pitches long, is routed through the bending device **210**. In some implementations, the bending device **210** has one or more protrusions **235**, **245** with a period ( $A$ ) that is matched to or nearly matched to (e.g., a threshold amount shorter than) a pitch of the graded index fiber **215**. At a neutral setting, the protrusions **235**, **245** of the bending device **210** are not in contact with the graded index fiber **215**, or are barely in contact with the graded index fiber **215**. Accordingly, in the neutral setting, the protrusions **235**, **245** are exerting no force on the graded index fiber **215**. In general, as described above, light launched on-axis at an entrance to the graded index fiber **215** leaves on-axis ( $\Delta x=0$ ), and exactly re-imaged. This fiber state is particularly useful to generate a nominally unperturbed, high-beam-quality output state.

In some implementations, the bending device **210** includes an actuation mechanism **225**, such as a micrometer knob and/or the like, that may be adjusted to cause a first section **230** of the bending device **210** to move toward a second section **240** of the bending device **210**. In some implementations, when the actuation mechanism **225** is adjusted to move the first section **230** toward the second section **240**, the protrusions **235**, **245** cause the graded index fiber **215** to bend in a wavelike pattern. In some implementations, the bending device **210** may be aligned such that one or more protrusions **235** of the first section **230** and one or more protrusions **245** of the second section **240** align with

odd quarter-pitch lengths of the graded index fiber **215**. In this way, when the protrusions **235**, **245** cause the graded index fiber **215** to bend in the wavelike pattern, a series of bends may be formed in the graded index fiber **215**, with a first bend in the series of bends aligned with a first quarter-pitch length of the graded index fiber **215** and each bend in the series of bends spaced a half-pitch length from an adjacent bend. Accordingly, the series of bends that are formed in the graded index fiber **215** are resonant with the intrinsic periodicity of the graded index fiber **215**. A small local bend is equivalent to introducing a tilt in the graded index fiber **215**, and because the Fourier transform of a tilt is an offset, the resulting effect is that a beam propagating through the graded index fiber **215** is gradually offset from the center of the graded index fiber **215** every half-pitch, as shown by plot **250**. The bends (or tilts) that occur every half-pitch are opposite in sign with respect to an axis of the graded index fiber **215**, which complements the image-flipping behavior of the graded index fiber **215** every half-pitch, and allows the offsets to add constructively. Accordingly, the total offset is controllable by the number of periods of the bending device **210**, and how much the two sections **230**, **240** of the bending device **210** move toward each other.

In some implementations, configuring the bending device **210** as shown in FIG. 2 may provide a bend with a strength that is independent of the focal length of the graded index fiber **215** to first order. In this way, the graded index fiber **215** can be freely chosen according to other system constraints, such as better mode-matching to an input fiber that is coupled to the graded index fiber **215** to provide a beam to the graded index fiber **215**, an output fiber that is coupled to the graded index fiber **215** to receive a beam after traveling through the graded index fiber **215**, and/or the like. In such cases, the period of the bend apparatus **210** (e.g., a periodicity of the protrusions **235**, **245** that cause the bends to be formed in the graded index fiber **215**) may be adjusted to correspond to the pitch of the graded index fiber **215**. In general, beam-shifting behavior of the bending device **210** is not strongly dependent on the precise shape of the periodic curve induced in the graded index fiber **215**. For example, the graded index fiber **215** may be bent in a sinusoidal pattern or another smoothly-varying oscillating curve, an alternating sequence of circular arcs, a sequence of straight or near-straight segments connected by sharp bends near the odd quarter-pitch positions, and/or the like. For example, the graded index fiber **215** may have a natural elastic bending shape when bent by near-point-contact actuators as shown in FIG. 2, which creates a smoothly-varying curve that is close to sinusoidal.

In one numerical example of the bending device **210**, an input beam provided by an input fiber may have a spot diameter of 50 microns and a divergence of 0.1 radians. Using a fused-silica graded index fiber **215** with a focal length of 750 microns and a numerical aperture (NA) of 0.21, and accounting for the stress-optic effect induced by the bends in the graded index fiber **215**, using four alternating bends (e.g., corresponding to two pitches of the graded index fiber **215**, as shown in FIG. 2) of 2.4 degrees apiece, spaced by a half-pitch length of 3.5 mm, may generate 100 microns of beam position offset, which is a practical and useful amount in comparison with the actual beam size of 50 microns. The actual bend angle of 2.4 degrees is relatively small and straightforward to actuate upon the graded index fiber **215** without causing damage to the graded index fiber **215** or requiring complicated fiber handling or geometry.

In some implementations, two multi-bend devices **210** can be cascaded, one following the other, with the multi-

bend devices **210** oriented in perpendicular orientations with respect to one another. For example, with an axis of the graded index fiber **210** arranged in a direction *z*, a first multi-bend device **210** may operate in an *x-z* plane and a second multi-bend **210** may operate in a *y-z* plane. Accordingly, the two multi-bend devices **210** may be adjusted independently to allow a user to displace a beam arbitrarily in the *x-y* plane, which provides a useful capability in many applications where a rasterable or addressable beam position is desired. Additionally, or alternatively, the two-dimensional addressing capability may be realized using a single multi-bend device **210** that can be actuated in any lateral desired direction. For example, the bending device **210** illustrated in FIG. 2 may additionally be rotatable around the fiber axis (e.g., using the rotation mechanism). Additionally, or alternatively, the actuating surfaces that touch the graded index fiber **215** may be small rings or small holes in flat, stacked tabs that can move the graded index fiber **215** in two dimensions at every actuator. The applied motion of the rings or holes may be adjustable in both an *x* orientation and a *y* orientation using two-dimensional adjustment stages rather than the one-dimensional stage illustrated in FIG. 2.

In some implementations, the bending device **210** is made to a high precision, as simulations indicate that the desired deflections are on the order of 10  $\mu\text{m}$ . Thus, the protrusions **235**, **345** may be fabricated to be precisely the same height, or at least have a precise mirroring relationship between the respective sections. For example, in some implementations, the bending device **210** may be fabricated to a high precision using wire electrical discharge machining and/or the like.

As indicated above, FIG. 2 is provided as one or more examples. Other examples may differ from what is described with regard to FIG. 2. For example, the number and arrangement of components shown in FIG. 2 are provided as an example. In practice, the arrangement shown in FIG. 2 may include additional components, fewer components, different components, or differently arranged components than those shown in FIG. 2. Additionally, or alternatively, a set of components (e.g., one or more components) in FIG. 2 may perform one or more functions described as being performed by another set of components in FIG. 2.

FIG. 3 is a diagram of one or more example implementations **300** of multiple bending devices arranged in a cascaded configuration. For example, as shown in FIG. 3, an input fiber **310** is coupled to a first bending device **320** and a second bending device **330** arranged in a cascaded configuration with a quarter-pitch graded index fiber **340** between the two bending devices **320**, **330**. In some implementations, the bending devices **320**, **330** may work on the same axes, perpendicular axes, or another mutual angle. For example, in FIG. 3, the bending devices **320**, **330** are arranged to work on perpendicular axes. Accordingly, the first bending device **320** may control an angle at which a beam leaves the quarter-pitch graded index fiber **340** in a *y* direction, and the second bending device **330** may control a spatial offset of the beam in an *x* direction. Combining the two bending devices **320**, **330** with the quarter-pitch graded index fiber **340** between the two bending devices **320**, **330** allows for control of both beam offset and beam deflection angle (e.g., near-field and far-field, respectively) on perpendicular axes, thereby generating skew light rays. If the two bending devices **320**, **330** are oriented on the same axis, the two bending devices **320**, **330** may generate meridional light rays, again with independent adjustment of both the beam offset and deflection angle. In some implementations, the quarter-pitch graded index fiber **340** between the two bending devices **320**, **330** may be the same as in a multi-bend

device, or different, and/or the quarter-pitch graded index fiber **340** may include multiple graded index elements that have a net action equivalent to one quarter-pitch graded index element.

In some implementations, the two stages **320**, **330** may be combined into one multi-bend device, where the graded index fiber **340** can be bent at every quarter-pitch rather than every odd quarter-pitch. In this case, the odd quarter-pitch bends may adjust the beam offset, and the even quarter-pitch bends may adjust the beam angle, measured from the output end in the event of a total length that is not an integer number of half-pitches. If the odd quarter-pitch bends are oriented perpendicularly to the even ones, then the overall bent fiber shape will be approximately helical and the output light will be skew. On the other hand, the output light will be meridional if the two sets of bends are parallel. With typical quarter-pitch lengths on the order of one millimeter or less, such a device may require an intricate actuation system, especially if the design objective is to provide full two-dimensional addressability in both the beam offset and beam deflection. Furthermore, in order to provide equal sensitivity for both offset and deflection, the graded index fiber **340** may have a focal length that causes a quarter-pitch beam size to be roughly the same as the size of an input beam provided by the input fiber **310**. Accordingly, for beam sizes of interest, the graded index fiber **340** may have a focal length of a few hundred microns. Additionally, or alternatively, the input beam size may be adjusted first (e.g., using a single quarter-pitch graded index fiber of suitable focal strength) to change the beam size to a desired new beam size, and a more preferred focal length of the extended graded index fiber can then be used for the bend array.

In some implementations, as described herein, the bends formed in the graded index fiber **340** may have any periodic bend shape with a bend period equal or approximately equal to a pitch of the graded index fiber **340**. In this way, the bends formed in the graded index fiber **340** can be used to manipulate the spatial properties of light carried by the graded index fiber **340**. In some implementations, the bending can be two-dimensional (e.g., in the *x-z* plane, where *z* is the average propagation direction, such as a simple sinusoid), or the bending can be three-dimensional (e.g., in *x*, *y*, and *z* directions, such as a circular helix, an elliptical helix, a more complicated three-dimensional shape that is periodic in the *z* direction, and/or the like). In some implementations, the bend period can be exactly matched to the pitch of the graded index fiber, or the bend period may be nearly matched to the pitch of the graded index fiber by  $\pm 25\%$ , by  $\pm 10\%$ , by  $\pm 3\%$ , and/or the like. Accordingly, in order to be matched or nearly matched to the pitch of the graded index fiber, a deviation between the bend period and the pitch of the graded index fiber may be required to satisfy (e.g., be less than and/or equal to) a threshold (e.g.,  $\pm 10\%$  or less). In some implementations, the bending device can, depending on the bend shape, manipulate the beam in the near-field (offset position), far-field (beam pointing direction), or both. In this way, forming bends in the graded index fiber **340** that are matched or nearly matched to the pitch of the graded index fiber **340** provide more versatility than adiabatic bending, which is generally limited to manipulating the near-field only.

Furthermore, in some implementations, a single bend may be formed in the graded index fiber **340**. In general, when a single bend is used, the single bend is substantially equal to or shorter than a half-pitch of the graded index fiber **340**, and the single bend is centered on a position in the graded index fiber **215** at least one-quarter-pitch away from an end of the

graded index fiber **215**. In such cases, some implementations described herein may enhance the bend effect substantially, compared to adiabatic bending. For example, in some implementations, a spliced assembly may include an input fiber to provide a beam, a graded index fiber that is coupled to the input fiber and one-half pitch in length relative to the imaging pitch length of the graded index fiber, and an output fiber capable of receiving a modified beam position from the graded index fiber, with a bend being applied to the graded index fiber, centered on, and strongest at, the middle of the graded index fiber. In some implementations, the bend may or may not extend into the input and/or output fibers, but may generally be weaker in the input and/or output fibers than in the graded index fibers in order to minimize bend stress applied to the splice points. In this case, the spliced assembly may differ from typical adiabatic-bent fibers because the majority of the bend should be equal in length, or shorter, than a half-pitch of the graded index fiber, which would typically be approximately 1-5 mm, and the strongest bend point would be applied not at the output splice point but approximately one quarter-pitch before the output splice, if the objective is to shift the near field only, similar to the adiabatic bend.

In some implementations, an optical system may include an actuation mechanism that allows a bend shape to be adjusted, thereby enabling at least two states of the output beam (e.g., an unperturbed state and a modified state). However, in the simplest case, a static periodic bend shape may be imparted to the graded index fiber **340** such that a given input state is statically transformed into a different output state (e.g., a different beam position and/or beam pointing direction than the input). One example of such a device may include an all-in-fiber rotary beam generator, where the induced fiber bend shape may be helical, and the output beam may be simultaneously offset from the fiber axis and tilted perpendicular to the offset, developing a skew character and orbital angular momentum. If the graded index fiber **340** were to be spliced to an output step-index or ring-index fiber with a radius matched to the spatial offset and an NA matched to the beam tilt angle, then the offset, skew beam would be captured and maintained in a rotating beam. This static rotary beam generator may be realized in an integrated format by fabricating a fiber preform that includes a graded index core that is offset from the fiber center axis, and spinning the fiber during the draw process so that the offset core actually follows a helical path (even though the outside of the fiber may appear straight). If the helical pitch, as determined by the spin rate relative to the draw rate during the fiber drawing process, equals or nearly equals the graded index pitch, then the helical-core fiber can generate a static lateral offset and beam deflection (e.g., a skew beam carrying orbital angular momentum), which may create an annular, rotary beam when the graded index fiber **340** is coupled into an output fiber (e.g., a step-index or ring fiber) of the appropriate diameter and NA to guide the rotary beam. In this way, some implementations described herein may produce a rotary beam that is compact and simple to manufacture. For example, the structure may be only a few millimeters or centimeters long, would not require tapering, would have a straightforward fiber preform fabrication, and may provide an efficient conversion to a rotary beam in terms of both power and brightness.

In some implementations, different options may be used as actuation mechanisms to provide two or more output states in addition to and/or as alternatives to the actuation mechanisms described above. For example, in some implementations, an actuation mechanism may provide full

addressability by controlling a two-dimensional transverse position of the graded index fiber at every half-pitch position, every quarter-pitch position, using an array of micro-manipulators, and/or the like. In another example, an actuation mechanism may be arranged to switch between a straight fiber shape and a helical fiber shape by holding the graded index fiber straight and slightly tensioned to provide the straight state, and twisting the graded index fiber while providing slight slack in the tension, such that the graded index fiber adopts a helical state with a pre-determined pitch. In another example, switching between a straight shape and a helical fiber shape may be enabled by twisting the graded index fiber around a second (non-optical) fiber of suitable diameter and stiffness with a predetermined number of turns, and either tensioning the optical fiber while slackening the non-optical fiber to provide the straight fiber state, or slackening the optical fiber while tensioning the non-optical fiber, to force the optical fiber into a helical conformation.

As indicated above, FIG. **3** is provided as one or more examples. Other examples may differ from what is described with regard to FIG. **3**. For example, the number and arrangement of components shown in FIG. **3** are provided as an example. In practice, the arrangement shown in FIG. **3** may include additional components, fewer components, different components, or differently arranged components than those shown in FIG. **3**. Additionally, or alternatively, a set of components (e.g., one or more components) in FIG. **3** may perform one or more functions described as being performed by another set of components in FIG. **3**.

FIGS. **4A-4C** illustrate example plots **400**, **410**, **420** related to a propagation length of a graded index fiber manipulated using one or more bending devices and/or one or more methods described herein. For example, as shown in FIG. **4A**, plot **400** illustrates a ray trace within a graded index fiber, showing a single ray propagating near an integer number of pitches. The source NA is 0.1. As shown in FIG. **4B**, plot **410** shows a lowest-order linearly polarized fundamental mode (LP<sub>01</sub>) of a 50  $\mu\text{m}$  and 0.22 NA step index fiber launched into different graded index fibers, which propagates a certain number of pitches. Furthermore, referring to FIG. **4C**, plot **420** shows how the “aberrations” of even a perfect graded index fiber affect the beam based on changing a spot size. A higher order mode of the same input fiber propagates through a certain number of pitches in the same graded indexes. Because this mode is less well size-matched to the graded indexes, the higher-order mode experiences more aberrations per pitch and expands faster.

Accordingly, one challenge of the bending devices and methods described herein is to achieve a precise length for the graded index fiber. If the length of the graded index fiber is significantly longer or shorter than an integral number of pitches, the input beam may have a “fuzzed out” image, with power at higher radii, which may incur a penalty in brightness (BPP) when coupled into a delivery fiber. As shown in FIG. **4A**, for tight size tolerances of approximately 5 micrometers ( $\mu\text{m}$ ), the length tolerance is independent of the graded index fiber focal length, and depends only on the input beam NA. For larger tolerances, the focal length may be a factor, with smaller focal lengths being more forgiving. The most forgiving configuration is to choose a graded index focal length that generates exactly the same spot size in both the near and far field (e.g., to size-match the graded index to the input beam). For an input beam radius ( $w$ ) and a divergence ( $\theta$ ), the appropriate graded index focal length is  $f=w/\theta$ . In this case, the beam does not change size while propagating (although a shape of the beam may oscillate subtly). In this case, the length of the graded index fiber is

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not critical, nor is the position of the beginning of the bend array with respect to the beginning of the graded index fiber. However, the period of the bend array is well-matched to the graded index pitch, and the final bend controlled in position relative to the end of the graded index fiber, so that the desired manipulation of the near and/or far fields is achieved.

Furthermore, an additional design consideration is that graded index “lenses” have aberrations, akin to free space elements. For example, even a graded index fiber with a perfect parabolic refractive index profile does not achieve a precise image every pitch, but rather has small errors that accumulate as more pitches are used. These errors depend strongly on the NA and size of the input beam. For example, if the input is a single fundamental mode in a 50  $\mu\text{m}$  diameter 0.22 NA step index fiber, the input can be almost perfectly reimaged after even 100 pitches in a graded index of the correct focal length, as shown in FIG. 4B. However, choosing a different mode in that input fiber, which has a poorer overlap to a corresponding mode in the graded index fiber, aberration per pitch grows progressively larger, as shown in FIG. 4C, even if the fiber length is chosen perfectly, for the same graded index fibers which maintained the spot size of the LP01 mode group of the input fiber. Generally, for a given input fiber, as the NA increases, the number of graded index pitches before significant aberration occurs will decrease. This is mathematically analogous to using a chain of lenses, each of which has a small amount of spherical aberration. Accordingly, in some implementations, a quantity of pitches in a length of the graded index fiber may be chosen to satisfy a threshold value that is based on one or more metrics related to errors that accumulate per-pitch of the graded index fiber. For example, as shown in FIG. 4C, aberrations significantly increase after a propagation length of approximately ten (10) pitches, whereby the series of bends may be formed in a length of graded index fiber that includes ten or fewer pitches in one example.

In some implementations, the exact length of the graded index fiber may not be an integral number of pitches in applications where maintaining brightness is desired. In some implementations, a device length may be chosen to minimize the spot size, rather than to provide a perfect integral number of pitches (akin to aligning a free space system to the circle of least confusion, as opposed to the paraxial focus). Moreover, dependent on the source, small modifications may be made to the refractive index profile to correct for different aberrations. In this way, the refractive index profile design would not be precisely parabolic, but a slightly different function, while still qualitatively a graded index.

Furthermore, aberration consideration may impact the number of periods of perturbation used. A high NA source may only afford a small number of pitches before the beam “fuzzes out,” while a lower NA source may use more pitches. In addition, the required deflection and tolerance on the micrometer stage may be a factor. In an automated system, the micrometers may be replaced with piezoelectrics or similar, enabling sub-second actuation. Additionally, some implementations described herein may have a mechanism to change the effective length to avoid excessive cleaving and polishing to achieve a precise length (e.g., by heating, longitudinal stress, compressive stress, and/or the like to vary the optical path length).

As indicated above, FIGS. 4A-4C are provided as one or more examples. Other examples may differ from what is described with regard to FIGS. 4A-4C.

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FIG. 5 is a flowchart of an example process 500 for applying a set of bends in a graded index fiber using one or more bending devices.

As shown in FIG. 5, process 500 may include routing a graded index fiber through one or more bending devices, wherein the one or more bending devices comprise one or more protrusions that have a periodicity matched to or nearly matched to a pitch of the graded index fiber (block 510). For example, in some implementations, a graded index fiber 100, 215, 340, and/or the like may be routed through one or more bending devices 210, 320, 330, and/or the like, as described above. In some implementations, the one or more bending devices 210, 320, 330, and/or the like comprise one or more protrusions 235, 245, and/or the like that have a periodicity matched to or nearly matched to a pitch of the graded index fiber 100, 215, 340, and/or the like.

As further shown in FIG. 5, process 500 may include actuating a first section of the one or more bending devices to move towards a second section of the one or more bending devices such that the one or more protrusions cause a series of bends to be formed in the graded index fiber, wherein the periodicity of the one or more protrusions causes the series of bends to have a bend period matched to or nearly matched to the pitch of the graded index fiber (block 520). For example, in some implementations, a first section 230 of the one or more bending devices 210, 320, 330 may be actuated to move towards a second section 240 of the one or more bending devices 210, 320, 330 such that the one or more protrusions 235, 245 cause a series of bends to be formed in the graded index fiber 100, 215, 340, and/or the like. In some implementations, the periodicity of the one or more protrusions 235, 245 causes the series of bends to have a bend period matched to or nearly matched to the pitch of the graded index fiber 100, 215, 340, and/or the like.

Process 500 may include additional implementations, such as any single implementation or any combination of implementations described below and/or in connection with one or more other processes and/or implementations described elsewhere herein.

For example, in a first implementation, the one or more bending devices may comprise a first bending device 320 arranged to cause a first series of bends in the graded index fiber in a first orientation, and a second bending device 330, following the first bending device 320, to cause a second series of bends in the graded index fiber in a second orientation.

In a second implementation, alone or in combination with the first implementation, the first series of bends in the first orientation and the second series of bends in the second orientation may be perpendicular to one another or parallel to one another.

In a third implementation, alone or in combination with one or more of the first and second implementations, the first series of bends manipulate a beam traveling through the graded index fiber in a near-field, and the second series of bends manipulate the beam traveling through the graded index fiber in a far-field.

In a fourth implementation, alone or in combination with one or more of the first through third implementations, process 500 includes rotating the one or more bending devices with respect to the graded index fiber, where the periodicity of the one or more protrusions is shorter than the pitch of the graded index fiber, and rotating the one or more bending devices with respect to the graded index fiber elongates the bend period to match or to nearly match the bend period to the pitch of the graded index fiber.

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In a fifth implementation, alone or in combination with one or more of the first through fourth implementations, the series of bends are formed in the graded index fiber in two dimensions or in three dimensions.

Although FIG. 5 shows example blocks of process 500, in some implementations, process 500 may include additional blocks, fewer blocks, different blocks, or differently arranged blocks than those depicted in FIG. 5. Additionally, or alternatively, two or more of the blocks of process 500 may be performed in parallel.

The foregoing disclosure provides illustration and description, but is not intended to be exhaustive or to limit the implementations to the precise forms disclosed. Modifications and variations may be made in light of the above disclosure or may be acquired from practice of the implementations.

As used herein, satisfying a threshold may, depending on the context, refer to a value being greater than the threshold, greater than or equal to the threshold, less than the threshold, less than or equal to the threshold, equal to the threshold, not equal to the threshold, and/or the like.

Even though particular combinations of features are recited in the claims and/or disclosed in the specification, these combinations are not intended to limit the disclosure of various implementations. In fact, many of these features may be combined in ways not specifically recited in the claims and/or disclosed in the specification. Although each dependent claim listed below may directly depend on only one claim, the disclosure of various implementations includes each dependent claim in combination with every other claim in the claim set.

No element, act, or instruction used herein should be construed as critical or essential unless explicitly described as such. Also, as used herein, the articles “a” and “an” are intended to include one or more items, and may be used interchangeably with “one or more.” Further, as used herein, the article “the” is intended to include one or more items referenced in connection with the article “the” and may be used interchangeably with “the one or more.” Furthermore, as used herein, the term “set” is intended to include one or more items (e.g., related items, unrelated items, a combination of related and unrelated items, and/or the like), and may be used interchangeably with “one or more.” Where only one item is intended, the phrase “only one” or similar language is used. Also, as used herein, the terms “has,” “have,” “having,” or the like are intended to be open-ended terms. Further, the phrase “based on” is intended to mean “based, at least in part, on” unless explicitly stated otherwise. Also, as used herein, the term “or” is intended to be inclusive when used in a series and may be used interchangeably with “and/or,” unless explicitly stated otherwise (e.g., if used in combination with “either” or “only one of”).

What is claimed is:

1. An optical assembly, comprising:
  - an input fiber to provide a beam; and
  - a graded index fiber, coupled to the input fiber, having a refractive index profile that causes the beam to be re-imaged in the graded index fiber with a regular period having a pitch length, wherein the graded index fiber comprises a set of bends that have a bend period matched to or nearly matched to the pitch length of the graded index fiber.
2. The optical assembly of claim 1, wherein the regular period of the beam and the set of bends applied to the graded index fiber are sinusoidal.

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3. The optical assembly of claim 1, wherein the set of bends comprises one or more bends in a first orientation and one or more bends in a second orientation.

4. The optical assembly of claim 3, wherein the one or more bends in the first orientation control an angle at which the beam exits the graded index fiber on a first axis, and wherein the one or more bends in the second orientation control a spatial offset of the beam on a second axis.

5. The optical assembly of claim 1, wherein the graded index fiber comprises a quantity of pitch lengths, and wherein each bend in the set of bends is spaced a half-pitch length from an adjacent bend in the set of bends.

6. The optical assembly of claim 1, wherein the graded index fiber comprises a quantity of pitch lengths, and wherein a first bend in the set of bends is aligned with a first quarter-pitch length of the graded index fiber.

7. The optical assembly of claim 1, wherein each bend in the set of bends has an opposite sign from an adjacent bend in the set of bends with respect to an axis of the graded index fiber.

8. The optical assembly of claim 1, wherein the set of bends comprises only a single bend that is centered on a position of the graded index fiber that is at least one quarter-pitch away from an end of the graded index fiber.

9. The optical assembly of claim 1, wherein a quantity of pitch lengths in the graded index fiber satisfies a threshold value that is based on one or more metrics related to errors that accumulate per-pitch of the graded index fiber.

10. A method, comprising:
 

- routing a graded index fiber through one or more bending devices, wherein the one or more bending devices comprise one or more protrusions that have a periodicity matched to or nearly matched to a pitch of the graded index fiber; and
- actuating a first section of the one or more bending devices to move towards a second section of the one or more bending devices such that the one or more protrusions cause a series of bends to be formed in the graded index fiber, wherein the periodicity of the one or more protrusions causes the series of bends to have a bend period matched to or nearly matched to the pitch of the graded index fiber.

11. The method of claim 10, wherein the one or more bending devices comprise a first bending device arranged to cause a first series of bends in the graded index fiber in a first orientation and a second bending device, following the first bending device, to cause a second series of bends in the graded index fiber in a second orientation.

12. The method of claim 11, wherein the first series of bends in the first orientation and the second series of bends in the second orientation are perpendicular to one another or parallel to one another.

13. The method of claim 11, wherein the first series of bends manipulate a beam traveling through the graded index fiber in a near-field, and wherein the second series of bends manipulate the beam traveling through the graded index fiber in a far-field.

14. The method of claim 10, further comprising:
 

- rotating the one or more bending devices with respect to the graded index fiber, wherein the periodicity of the one or more protrusions is shorter than the pitch of the graded index fiber, and wherein rotating the one or more bending devices with respect to the graded index fiber elongates the bend period to match or to nearly match the bend period to the pitch of the graded index fiber.

**15.** The method of claim **10**, wherein the series of bends are formed in the graded index fiber in two dimensions or in three dimensions.

**16.** A bending device, comprising:

an adjustment stage adapted to receive a graded index fiber, wherein the adjustment stage comprises a first section having a first set of protrusions and a second section having a second set of protrusions that have a periodicity matched to or nearly matched to a pitch of the graded index fiber; and

an actuation mechanism to cause the first section of the adjustment stage to move toward the second section of the adjustment stage such that the first set of protrusions and the second set of protrusions cause a series of bends to be formed in the graded index fiber.

**17.** The bending device of claim **16**, wherein the periodicity of the one or more protrusions causes the series of bends to have a bend period matched to or nearly matched to the pitch of the graded index fiber.

**18.** The bending device of claim **16**, wherein the first set of protrusions and the second set of protrusions exert no force on the graded index fiber when the first section of the adjustment stage and the second section of the adjustment stage are in a neutral state in which the graded index fiber is routed through the adjustment stage.

**19.** The bending device of claim **16**, further comprising: a rotation stage adapted to rotate the bending device with respect to the graded index fiber.

**20.** The bending device of claim **16**, wherein the actuation mechanism enables a shape of the series of bends to be adjusted such that a beam output by the graded index fiber has at least two states.

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